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LASER PULSE FORMATTING TO REDUCE THERMAL BLOOMING
BY AEROSOL VAPORIZATION

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16. average power of 2 MW, a pulsewidth of 1 μ sec, and a pulse repetition frequency of 10 Hz, the critical power at $d = 5$ m is 100 MW. This greatly alleviates the thermal blooming problem.

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INTRODUCTION

Propagation of ground-based, high-energy laser (HEL) beams through the atmosphere at a laser wavelength of $\lambda_L = 1.06 \mu\text{m}$ is limited by thermal blooming due to aerosol absorption. The scaling of critical laser power with beam diameter requires that the aperture size exceed 20 m for average laser powers of 100 MW.

Science Research Laboratory (SRL) has considered the resolution of this problem by vaporizing the aerosols with a designated laser for aerosol vaporization (LAV). In this report, the dependence of vaporization on fluence and wavelength will be described. A laser wavelength $\lambda_v = 1.06 \mu\text{m}$ and intensity of 10 MW/cm^2 yields a reduction in the atmospheric absorption by a factor of 5 at $2 \mu\text{sec}$, corresponding to 20 J/cm^2 of laser fluence. The best results are obtained at $\lambda_v = 0.248 \mu\text{m}$, which is the KrF laser wavelength. In this case, an intensity of 3 MW/cm^2 and a pulse duration of $1 \mu\text{sec}$, corresponding to a fluence of 3 J/cm^2 , yields a reduction by a factor of 50. Such a decrease in the absorption coefficient eliminates the difficulties associated with thermal blooming.

The dependence of the critical HEL power on the beam aperture diameter d has been determined in the presence and absence of LAV, assuming no wind shear. Without vaporization the scaling law is pessimistic—one can propagate less than 10 MW average power at $d = 10 \text{ m}$. If one uses a KrF laser at an average power of 2 MW, a pulsewidth of $1 \mu\text{sec}$, and a pulse repetition frequency (PRF) of 10 Hz, the critical power at $d = 5 \text{ m}$ is 100 MW. This greatly alleviates the thermal-blooming problem.

1.0 AMELIORATION OF THE THERMAL BLOOMING PROBLEM

The main obstacle for beam propagation of ground based, high energy lasers (HEL) is the thermal blooming in the atmosphere due to molecular and aerosol absorption. Even a small fraction of the laser energy deposited in the air, induces changes in the refractive index resulting in a significant beam spreading. This phenomena is referred to as thermal blooming. The laser wavelength is chosen in an atmospheric window where the absorption is small. For BMD application the current choice is $\lambda = 1.06 \mu\text{m}$. The laser can be tuned to a wavelength where there are no strong water vapor absorption lines and aerosol absorption dominates.

The HEL beam path in the atmosphere can be cleared by a designated laser for aerosol vaporization (LAV). Such a laser operates at an average power only a few percent of the HEL power. To minimize the LAV power one has to choose a wavelength at which the aerosol absorption coefficient (α) is large. At $\lambda = 1 \mu\text{m}$, $\alpha \simeq 10^{-7} \text{ cm}^{-1}$, while at $\lambda = 0.248 \mu\text{m}$, $\alpha \simeq 2 \times 10^{-6} \text{ cm}^{-1}$. As a result the vaporization fluence for a KrF laser is nearly 20 times smaller than for a Nd:glass laser. To vaporize the aerosols at $\lambda = 0.248 \mu\text{m}$ one needs a laser fluence $\geq 1 \text{ J/cm}^2$ and in this regime aerosol absorption dominates the saturated ozone absorption in the lower atmosphere.

The temporal format of the LAV should be consistent with the heat exchange time between the aerosols and the surrounding air, as well as the wind velocity. For typical dry aerosols the air is heated at times $\geq 1 \mu\text{sec}$ and the LAV should vaporize the particles in less than $1 \mu\text{sec}$. This determines the LAV pulse length. If the vaporization laser propagates in a guard-ring around the HEL beam, its pulse repetition frequency (PRF) is determined by the thickness of the guard-ring and the wind velocity. Typical parameters lead to a PRF of 10 Hz.

To reduce the thermal blooming and propagate 100 MW of HEL power at beam diameters in the range of 4m, one needs only 2 MW of LAV power. This is an excellent trade-off if one considers that in the absence of LAV only 10 MW of power can be transmitted to a relay mirror in space. The alternative to LAV is either a very large and expensive beam director ($d \geq 20 \text{ m}$) or a risky and unproven technology based on optical phase conjugation, i.e. Brillouin scattering or four-wave mixing.

Science Research Laboratory will propose to demonstrate the clearing of aerosols by a laser for aerosol vaporization in a series of laboratory experiments:

- Single pulse LAV
 - Determine the changes in the aerosol size distribution and the reduction in aerosol mass loading.
 - Determine the reduction in the aerosol absorption coefficient after vaporization.
- Repetitively pulsed LAV
 - Determine the reduction in thermal blooming in steady state.

2.0 THEORY OF AEROSOL VAPORIZATION

2.1 INTRODUCTION

Propagation of high power laser beams through the atmosphere gives rise to molecular and aerosol absorption which results in local heating. The air expands to restore pressure balance and the resulting density perturbation leads to a decrease in the local refractive index. The phase front of the HEL beam moves faster in regions of lower refractive index (n) and bends toward regions of larger n . The result is a thermal blooming of the beam in the cross wind direction and a tilt in the wind direction.⁽¹⁻²⁾ The propagation of a ground based laser beam to a relay mirror in space requires compensation for the deleterious effects of thermal blooming and atmospheric turbulence. This is achieved with a closed loop adaptive optics system.⁽³⁻⁵⁾ A beacon in space is used to probe the atmosphere and sense index of refraction perturbations which are measured at the transmitter on the ground. Phase compensation means that the conjugate of the incoming beacon phase be imposed on the outgoing laser beam with a deformable mirror consisting of actuators spaced a coherence length r_c apart. Such a system compensates very well for atmospheric turbulence with Strehl ratios in excess of 80%. The thermal blooming can be compensated only up to a critical laser power, P_c . The scaling law of P_c as a function of beam diameter (d), laser wavelength (λ) and absorption coefficient (α) is of the form, $P_c \sim d^a \lambda^b / \alpha$. The values of a and b are the subject of an active study with no consensus at the present time. The fact that P_c is inversely proportional to α is beyond dispute. It is clear, that despite uncertainties in the scaling law, the propagation of 100 MW of average GBL power necessary for BMD applications will result in unacceptably large aperture sizes. The only effective remedy is to reduce significantly the absorption coefficient α .

The laser wavelength is chosen in an atmospheric window, where α due to molecular and aerosol absorption is minimum. One of the atmospheric windows is near $1.06 \mu\text{m}$. At this wavelength the molecular absorption is dominated by the water vapor continuum. Experiments at SRL in the past few months have demonstrated that for $\lambda \simeq 1.057 \mu\text{m}$ there is a micro-window of 10 cm^{-1} width where α is of the order of 10^{-9} cm^{-1} . The results are shown in Figs. 1a and 1b. In Fig. 1b, the continuous line is a fit from FASCODE and the dots are the SRL data. By comparison, α from aerosol absorption in the $1 \mu\text{m}$ range and good visibility (23 km) is of the order of 10^{-7} cm^{-1} . If the GBL wavelength is in the water vapor absorption window, the aerosols are by far the dominant absorber. To reduce α we consider clearing the aerosols by vaporization with a designated laser for aerosol vaporization (LAV).

The particles, responsible for the absorption, range in size between $0.1 \mu\text{m}$ and $0.5 \mu\text{m}$.⁽⁶⁾ As they are heated by the laser they transfer the heat to the surrounding air on a time scale of $1 \mu\text{sec} - 10 \mu\text{sec}$.⁽⁷⁻⁸⁾ Efficient vaporization takes place when the laser heats the particles to the boiling point in a short time of the order of $1 \mu\text{sec}$ and this consideration determines the pulselength of LAV. The pulse format of the induction linac HEL is such that a single 50 nsec pulse can not heat the aerosols to the vaporization temperature. With a PRF of the order of 10 kHz the particles cool down between pulses and do not accumulate the heat. This is the main reason why the IL-HEL cannot vaporize

760 TORR, 22.9°C

TYPE	ABSORBERS (TORR)
H ₂ O	14.260
CO ₂	0.251
O ₃	2.3 X 10 ⁻⁵
N ₂ O	2.1 X 10 ⁻⁴
CO	5.7 X 10 ⁻⁵
CH ₄	1.2 X 10 ⁻³
O ₂	159.627

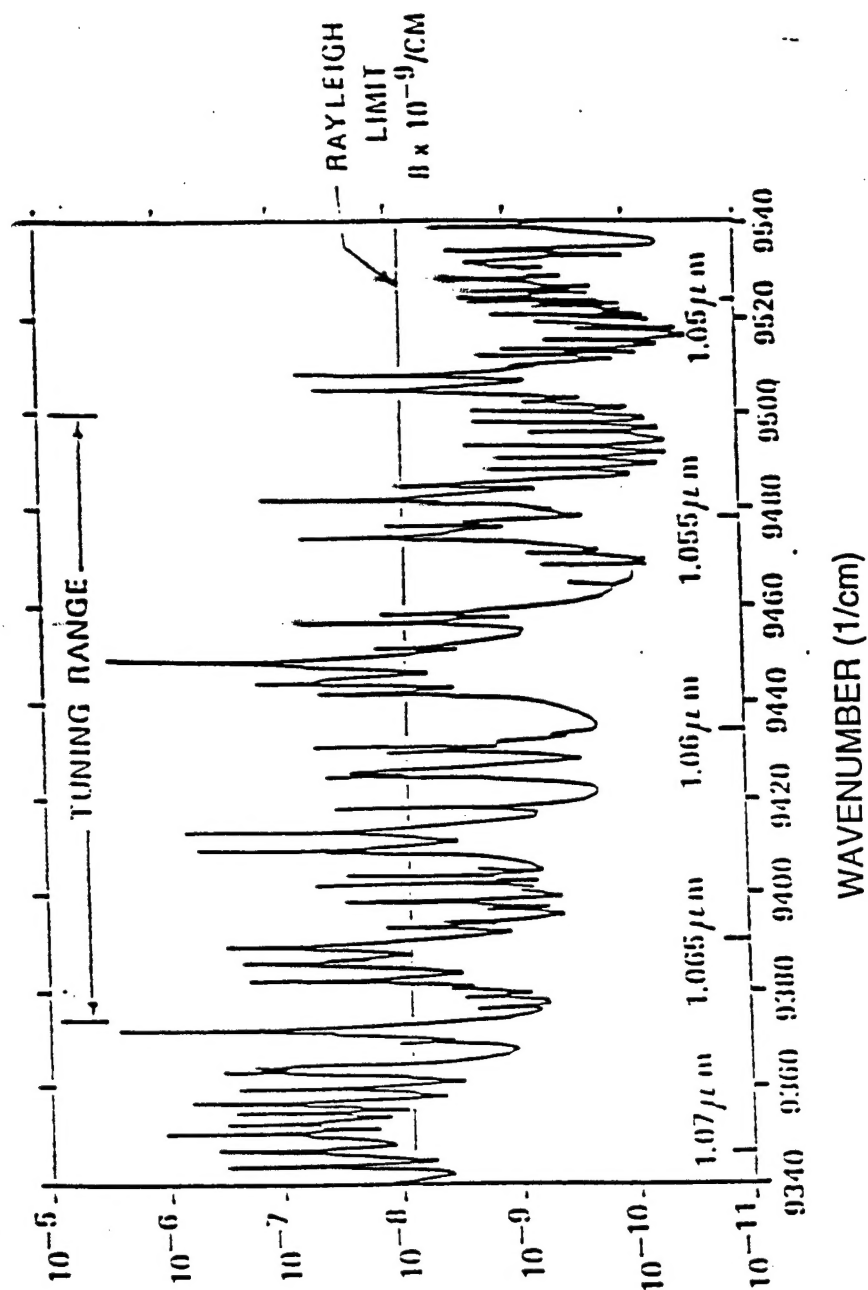


Figure 1a: Atmospheric absorption near 1.06 μm (FASCODE)

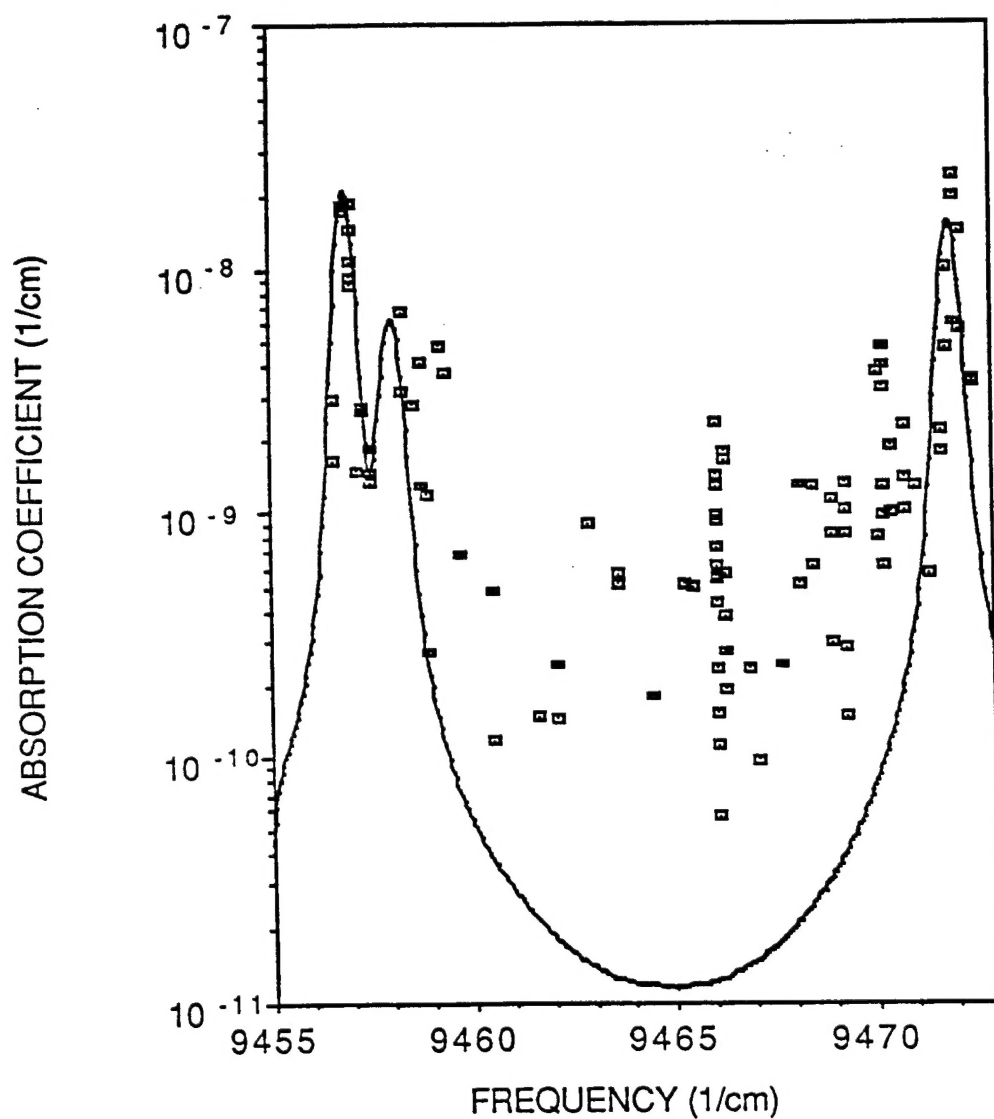


Figure 1b: Water vapor absorption in N_2 . $T=30^\circ C$, vapor pressure 14 Torr, total pressure 767 Torr. The discrete points are SRL measurements. The solid line is a FASCODE result convolved with the SRL line shape and normalized to a known line strength.

the aerosols. The heating of the particles is related also to the imaginary part of their refractive index, n_i . n_i is a sensitive function of λ . The HEL wavelength is chosen to minimize n_i and the absorption, while that of the LAV should be chosen at λ_v where n_i is large. From our calculations it appears that $\lambda_v = 0.248 \mu\text{m}$ is the optimum wavelength. This will insure that the power of the LAV beam is a small fraction of the power of the BMD-HEL beam. If one considers a LAV beam propagating in a guard-ring of thickness d_v surrounding the HEL beam, the PRF will be determined by V_w/d_v , where V_w is the wind velocity. With $V_w = 5 \text{ m/sec}$ and $d_v = 0.5 \text{ m}$ one finds $\text{PRF} = 10 \text{ Hz}$.

In this section the dynamics of single particle heating and vaporization is studied, and the critical laser fluence is determined. The change in size distribution and absorption coefficient during aerosol vaporization are found as function of fluence. The turbulence induced intensity scintillations of the LAV lead to phase distortions on a scale of the order of the coherence length of the LAV. Their effect on the propagation of the HEL beam is studied. The basic requirements for LAV are determined and its impact on the thermal blooming scaling and the overall system are evaluated.

2.2 HEATING AND VAPORIZATION OF THE AEROSOLS

The atmospheric aerosols have components of different chemical composition, index of refraction and sizes. The large particles with dimensions above $1 \mu\text{m}$ consist mostly of sand and are irregular in shape. However, their number is quite small ($< 100 \text{ particles/cm}^3$) and their imaginary index of refraction, n_i , is small. Their contribution to the absorption coefficient is considered negligible. The very small particles with $a \leq 0.05 \mu\text{m}$ are probably mostly carbon with large n_i , but their mass loading is negligible and their contribution to α will be considered small. The particles which are responsible for thermal blooming typically are in the range between $0.05 \mu\text{m}$ and $0.5 \mu\text{m}$. We shall assume that they are uniform and spherical in shape. Since the mean free path in the atmosphere is $0.05 \mu\text{m}$, one treats the process of heat transfer from the particles to the air as a conduction dominated diffusion process, i.e. the temperature in the air surrounding the particles is given by the heat diffusion equation,⁽⁷⁻⁸⁾

$$\rho_a C_a \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(K_a r^2 \frac{\partial T}{\partial r} \right) \quad (1)$$

ρ_a, C_a, K_a are the density, specific heat and thermal conductivity of the air and in our model they are assumed to be constant. The temperature inside the particle is considered uniform because its thermal conductivity is much greater than that of the air. Typical temperature equilibration times for particles of $1 \mu\text{m}$ radius are of the order of 10 nsec . Furthermore, the laser intensity inside the aerosol is assumed to be uniform and the effect of focusing of the light inside the particle is neglected. The conditions of a diffusion process and no focussing lead to larger threshold values for vaporization. Anomalous low intensity threshold values have been observed for particles with real part of the refractive index approaching 2, where focusing inside a sphere is occurring. In general, our analysis will conservatively estimate the vaporization threshold.

The boundary condition at the particle surface is

$$I\sigma_A = \frac{4\pi}{3}a^3C_p\rho_p\frac{\partial T}{\partial t} - 4\pi a^2K_a\frac{\partial T}{\partial r} - 4\pi a^2L_v\rho_p\frac{da}{dt}. \quad (2)$$

σ_A is the aerosol absorption cross section calculated from Mie theory,⁽⁹⁾ ρ_p, C_p, L_v are the particle density, specific heat and latent heat of vaporization, and I is the laser intensity. To determine the vaporization threshold, consider T just below the boiling point and neglect the last term in Eq. (2). Equation (1) with the condition (2) was solved analytically for a CW laser.⁽⁸⁾ The result can be extended to a laser pulse length τ_p . At the particle surface one finds

$$T(a, t) = T_o + \frac{I\sigma_A}{4\pi aK_a} \left\{ \theta(t) \left[1 - \exp\left(-\frac{t}{\tau_a}\right) \right] - \theta(t - \tau_p) \left[1 - \exp\left(-\frac{t - \tau_p}{\tau_a}\right) \right] \right\}, \quad (3)$$

where T_o is the ambient temperature, $\tau_a = a^2\rho_pC_p/3K_a$ is the equilibration time and $\theta(t)$ is the unit step function, $\theta(t) = 1$ when $t > 0$ and zero otherwise. The absorption cross section, σ_A is a function of aerosol radius, a , the laser wavelength, λ and the index of refraction, $n = n_r + in_i$. The latter is shown as a function of λ from 0.248 μm to 10 μm for representative dustlike and water-soluble aerosols. Note from Fig. 2 that the real part is between 1 and 1.5 for all wavelengths, except the range 9-10 μm , where focussing inside the aerosol is possible. The imaginary part, see Fig. 3, has peaks near the shortest and longest wavelengths. The absorption efficiency, $Q_A = \sigma_A/\pi a^2$, is calculated from Mie theory applied to dry aerosols at $\lambda = 0.248 \mu\text{m}$, 1.06 μm . The result is shown on Fig. 4. The regime at small radii, where $Q_A \propto a$ and $\sigma_A \propto a^3$ is called the Rayleigh regime and for calculating absorption it is determined by $a < \delta$, where $\delta = (2kn_i)^{-1}$ is the bulk absorption distance. At $\lambda = 1.06 \mu\text{m}$, $n_i = 8 \times 10^{-3}$, one has $\delta = 10 \mu\text{m}$ and the Mie theory result falls into the Rayleigh regime for $a \leq 5 \mu\text{m}$. At $\lambda = 0.248 \mu\text{m}$, $n_i = 3 \times 10^{-2}$, $\delta = 0.7 \mu\text{m}$ and the Rayleigh regime applies to particles of sizes up to 0.4 μm . Since the submicron particles dominate the absorption we treat the aerosols in the Rayleigh regime and write for σ_A ,

$$\sigma_A = \frac{\pi a^3}{\delta}. \quad (4)$$

The vaporization threshold is evaluated from Eq. (3) when $T(a, \tau_p) = T_v$, the vaporization temperature. In Fig. 5 the critical fluence, $F_c = I_c\tau_p$, is plotted as a function of τ_p for $T_v = 2500^\circ\text{C}$, different laser wavelengths and dry aerosols of the dominant size $a = 0.2 \mu\text{m}$. When $\tau_p < \tau_a$ the critical fluence is independent of pulselength. From Eq. (3) one can write ($\tau_p \ll \tau_a$),

$$F_c = \frac{T_v - T_o}{\sigma_A} \frac{4\pi a^3}{3} \rho_p C_p. \quad (5)$$

with σ_A in the Rayleigh regime and $T_v \gg T_o$ one finds

$$F_c = \frac{\lambda \rho_p C_p T_v}{3\pi n_i}. \quad (6)$$

As seen from Fig. 5, F_c is independent of τ_p for $\tau_p \leq 1 \mu\text{sec}$ because the equilibration time for 0.2 μm aerosols is $\tau_a = 1.3 \mu\text{sec}$. The threshold is proportional to $\lambda/n_i(\lambda)$ and

this quantity determines the effectiveness of LAV. Clearly, the KrF wavelength is the most effective with $F_c = 0.5 \text{ J/cm}^2$. In Fig. 6 the critical fluence $F_c(\tau_p)$ is plotted for dry aerosols of different sizes and $\lambda = 0.248 \text{ } \mu\text{m}$. Note that a fluence of 1 J/cm^2 at $\tau_p = 1 \text{ } \mu\text{sec}$ will vaporize all particles larger than $0.2 \text{ } \mu\text{m}$ in radius. Figures 5 and 6 illustrate also that lasers of longer pulselenghts require substantially larger fluencies of vaporization because the particles exchange heat with the air during the laser pulse. For example, at $\lambda = 1.06 \text{ } \mu\text{m}$, $\tau_p = 10 \text{ } \mu\text{sec}$, $a = 0.2 \text{ } \mu\text{m}$ the critical fluence exceeds 100 J/cm^2 , see Fig. 5. This important result will be used in the experiments proposed by SRL to combine a short pulse LAV and a long pulse probe laser of large fluence to achieve the required sensitivity in measuring the absorption coefficient α .

When $F > F_c$ a rapid evaporation takes place and the last term on the r.h.s. of Eq. (2) dominates. With σ_A given by Eq. (4) one can write⁽¹⁰⁾

$$\frac{da}{dt} = -\frac{\pi n_i I}{\lambda \rho_p L_v} a \quad (7)$$

The particle is reduced in size exponentially,

$$a = a_0 \exp\left(-\frac{F}{3F_v}\right) \quad (8)$$

where $F_v = \lambda \rho_p L_v / 3\pi n_i$ is the fluence vaporization rate. For dry aerosols typical values are $\rho_p = 2.3 \text{ g/cm}^3$ and $L_v = 4 \text{ kJ/g}$.

Table 1: Vaporization Fluence for Dustlike Aerosols at Different Wavelengths.

LAV Wavelength (μm)	Refractive Index of Aerosols	Vaporization Fluence (J/cm^2)
0.248	$1.52 + 3 \times 10^{-2} i$	0.8
1.06	$1.52 + 8 \times 10^{-3} i$	12
10.6	$1.62 + 0.12 i$	8

The reduction in particle size means reducing the mass loading of the aerosols and reducing α . To determine that effect we study the whole ensemble of particles of different sizes.

2.3 SIZE DISTRIBUTION OF THE AEROSOLS WITH VAPORIZATION

The size distribution of the aerosols has been the subject of extensive research in the past and it is continuing at the present time. It appears that the aerosols consist of at least 2 or 3 components with different distributions, ranging in size from $10^{-2} \text{ } \mu\text{m}$ to a few μm .

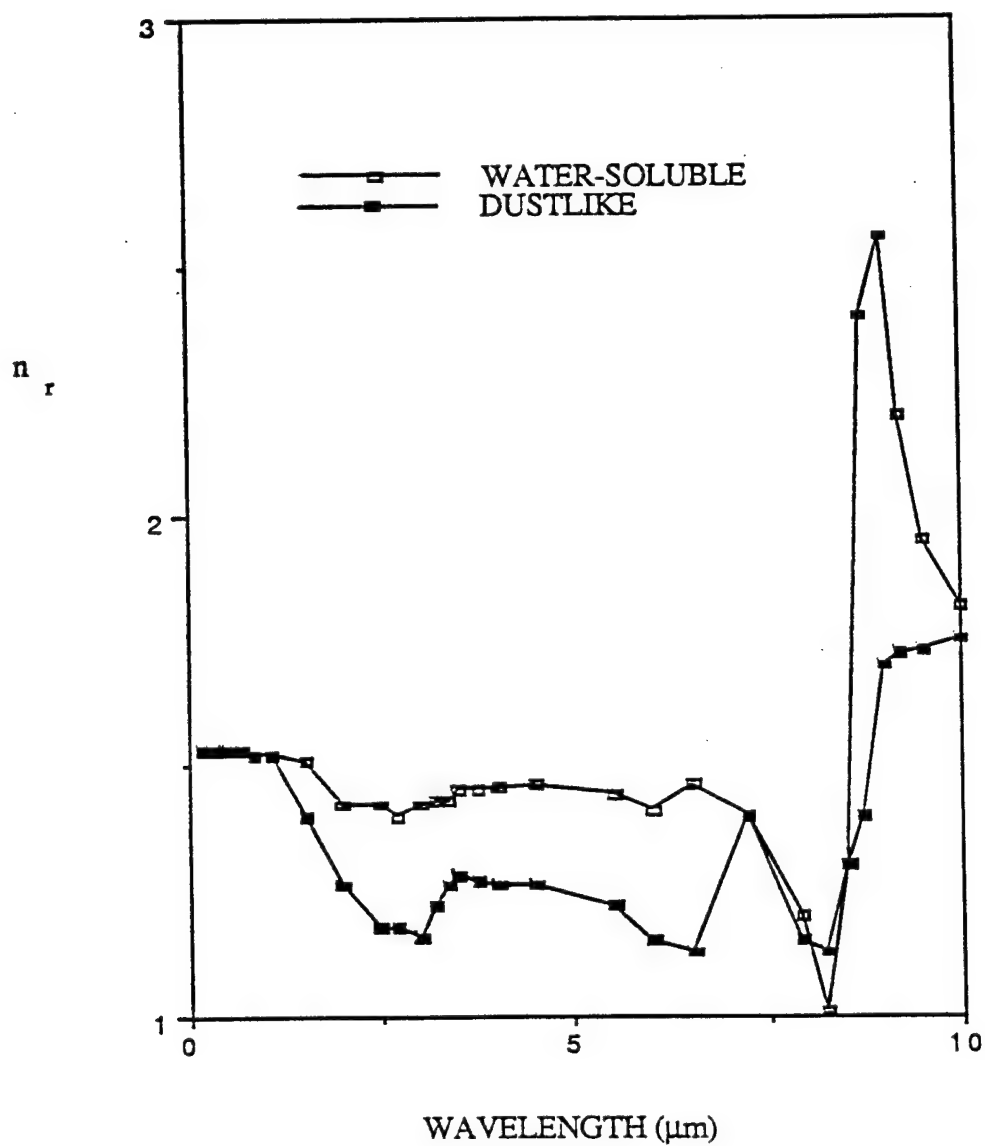


Figure 2: Real part of refractive index of aerosols

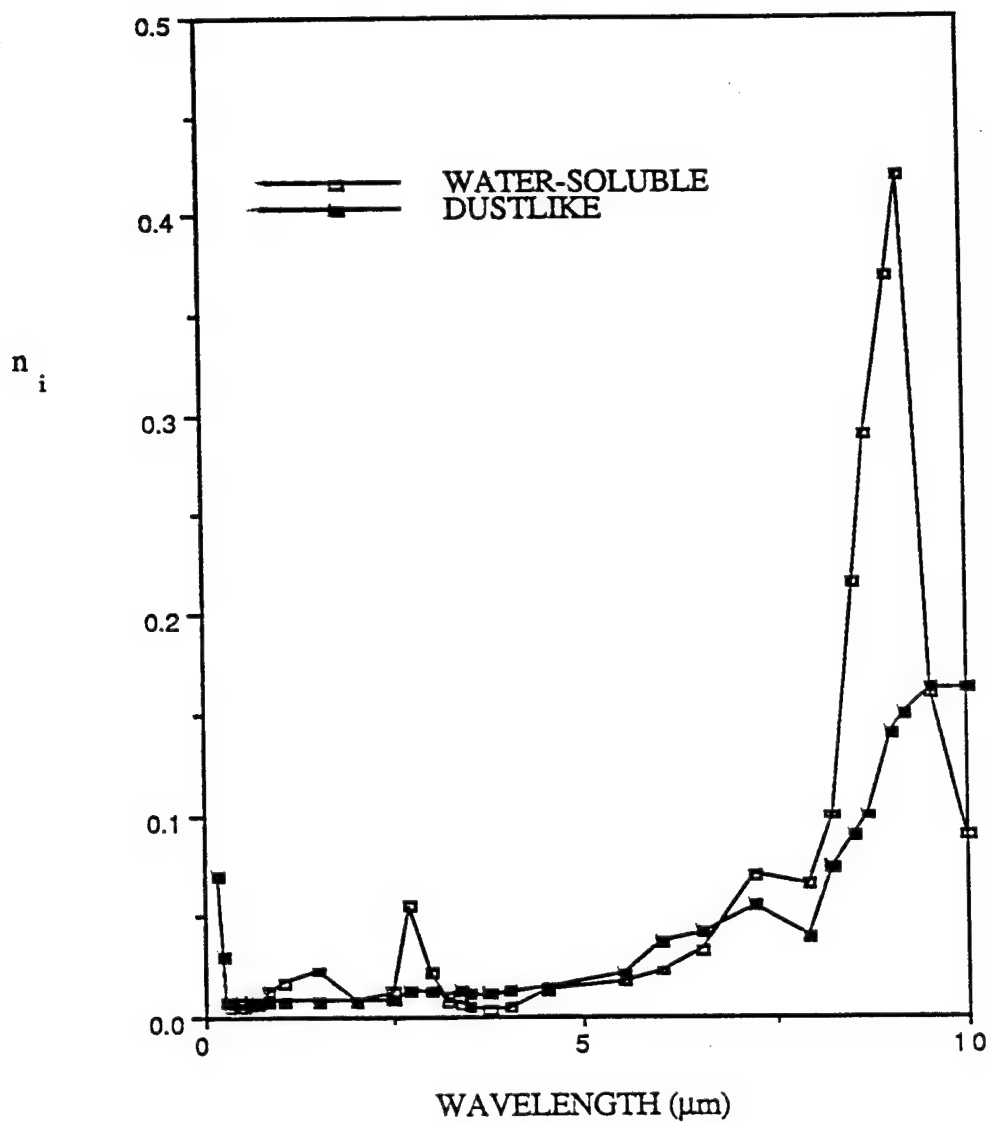


Figure 3: Imaginary part of refractive index of aerosols

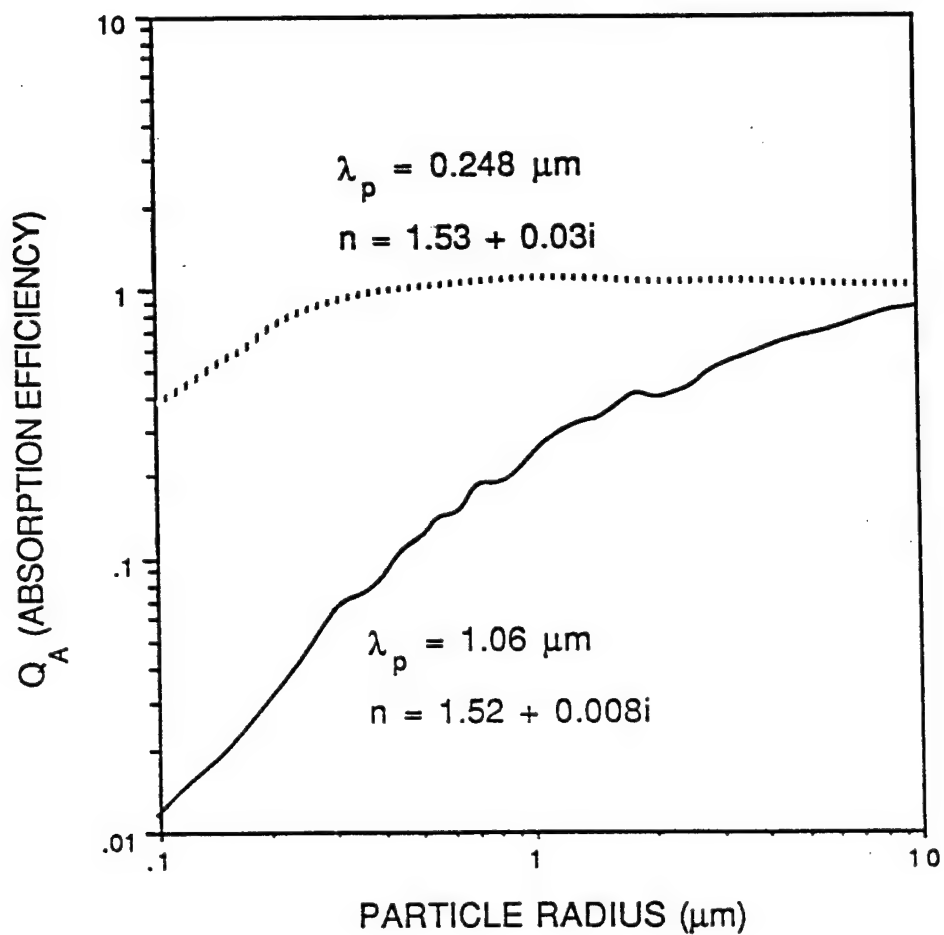


Figure 4: Absorption efficiency of dustlike spherical particles for Nd glass and KrF laser wavelengths

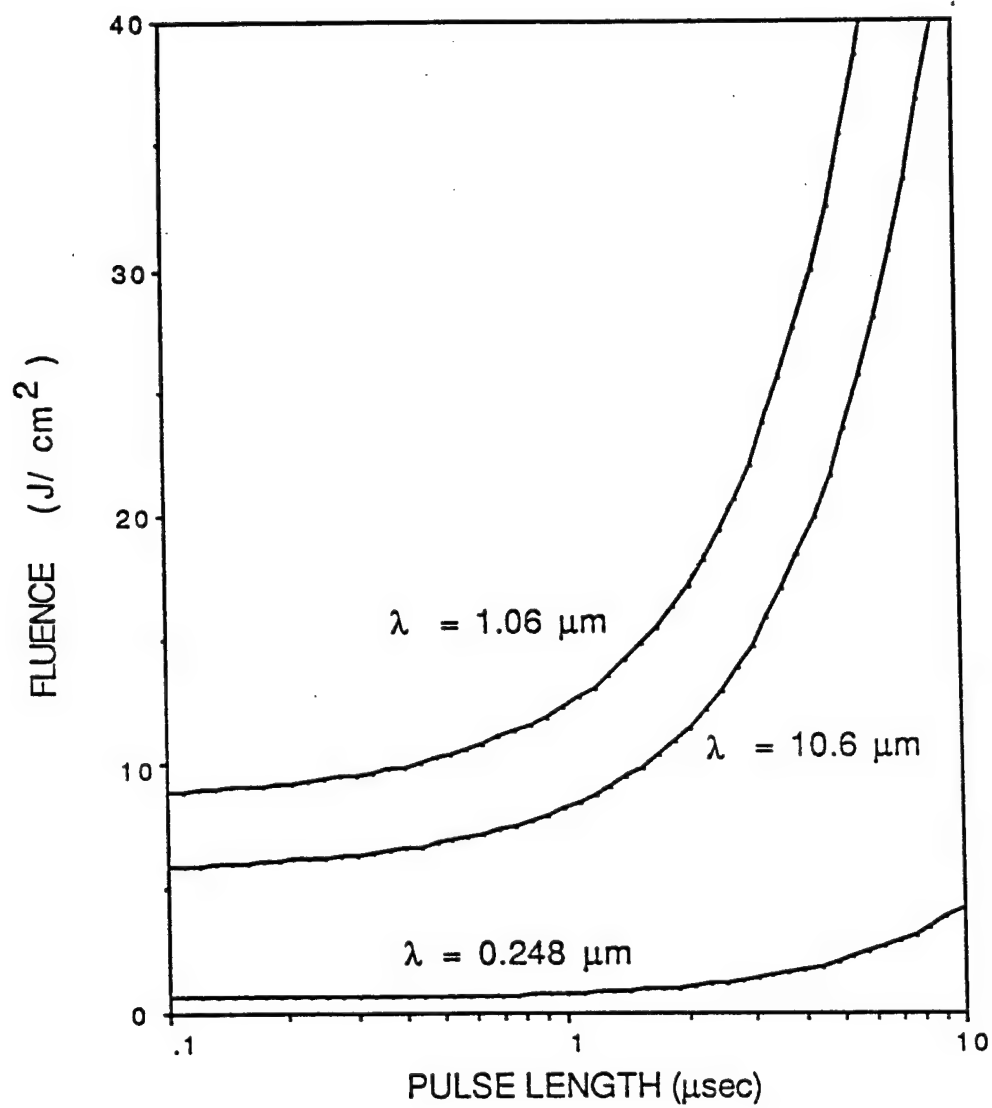


Figure 5: Critical fluence for aerosol evaporation

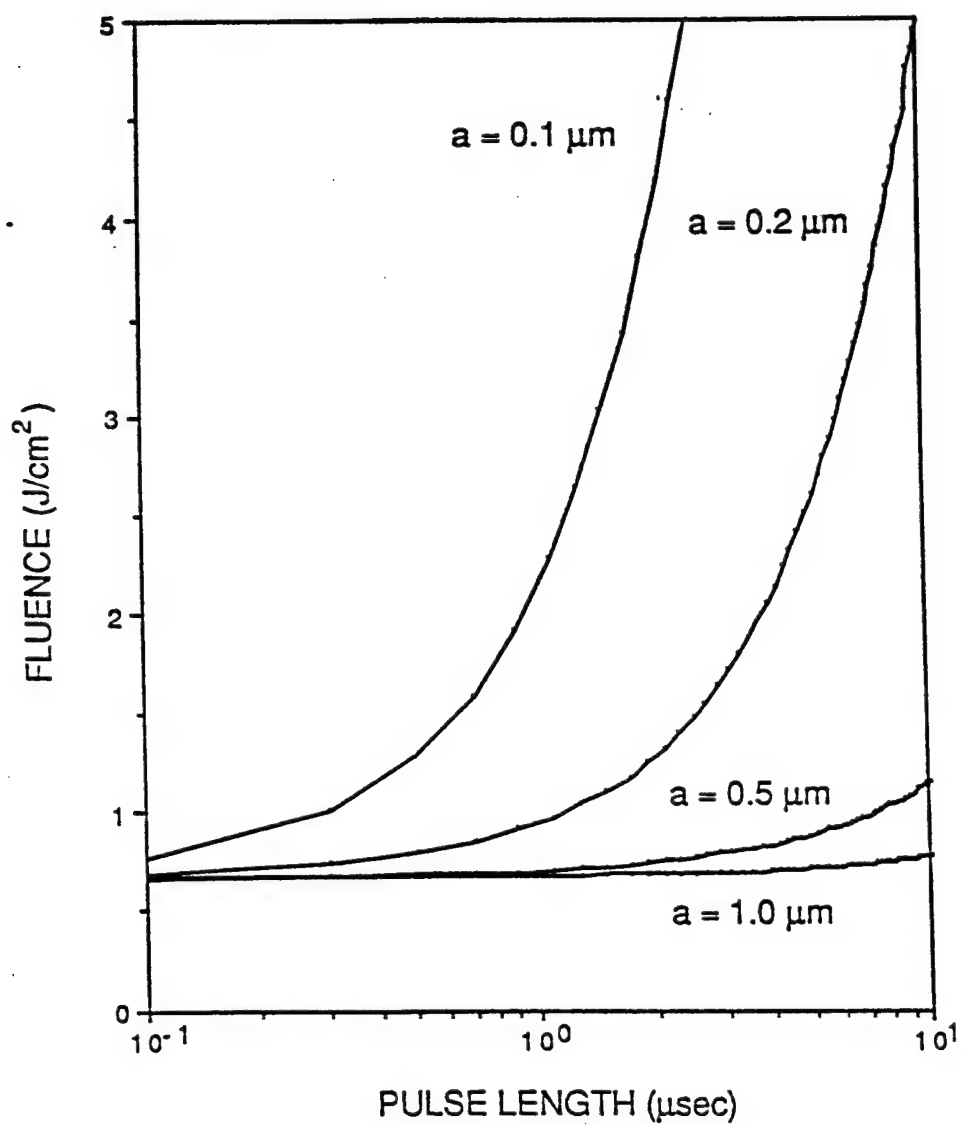


Figure 6: Critical fluence for aerosols of different size, $\lambda = 0.248 \mu\text{m}$

It is assumed that the submicron fraction is the most important for the optical properties of haze with the Yunge and modified gamma distributions being favored by researchers in this field. While the Yunge distribution, $f \sim a^{-4}$, fits well the data, it suffers from the drawback that without cutoffs it leads to divergent moments. For theoretical studies the modified gamma distribution function is preferable. It is given by⁽¹⁰⁾

$$f(a) = N_o \frac{4a^2}{a_o^3} \exp\left(-\frac{2a}{a_o}\right) \quad , \quad (9)$$

where a_o is the most probable size of the aerosols and N_o is the number of particles/cm³, $\int_0^\infty f(a)da = N_o$. Equation (9) has been used in the study of cloud clearance as a size distribution for the water droplets. Experimental results with a CO₂ laser have shown an excellent agreement with theory. The size distribution satisfies the equation⁽¹⁰⁾

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial a}(\dot{a}f) = 0 \quad (10)$$

It is assumed that during vaporization particles are not broken up into fragments and they do not disappear. The aerosols are only reduced in size and their number (N_o) is conserved. From Eqs. (8) and (10) one can write for f in terms of fluence and particle radius,

$$\frac{\partial f}{\partial F} - \frac{1}{3F_v} \frac{\partial}{\partial a}(af) = 0 \quad (11)$$

The solution of Eq. (11) with an initial distribution (9) is given by

$$f(a, F) = N_o \frac{4a^2}{a_o^3} \exp\left(\frac{F}{F_v}\right) \exp\left[-\frac{2a}{a_o} \exp\left(\frac{F}{3F_v}\right)\right] \quad (12)$$

At the present time there is no direct measurement of a size distribution function with vaporization. SRL proposes to do an experiment to measure f before and after vaporization and this will provide a crucial link to determine the vaporization mechanism and find the absorption coefficient α as a function of fluence.

2.4 ABSORPTION COEFFICIENT WITH AEROSOL VAPORIZATION

The absorption coefficient for the aerosols is determined from the absorption cross-section and the size distribution,

$$\alpha(F) = \int_0^\infty \sigma_A(a) f(a, F) da \quad (13)$$

From Eqs. (4) and (12) one obtains

$$\alpha(F) = \alpha_o \exp\left(-\frac{F}{F_v}\right) \quad (14)$$

where

$$\alpha_o = N_o \frac{30\pi^2 n_i a_o^3}{\lambda} \quad (15)$$

is the absorption coefficient in the absence of vaporization. Equation (14) is a central result of this proposal and shows why a fluence above the vaporization rate significantly decreases the aerosol absorption. Note that in the Rayleigh regime the absorption coefficient is proportional to the mass loading ($\sigma_A \sim a^3$). With vaporization the aerosol mass simply decreases as shown by (14), which is consistent with the exponential decrease in radius, see Eq. (8). This means that at $\lambda = 0.248 \mu\text{m}$ and fluence of 4 J/cm^2 the absorption coefficient is reduced by two orders of magnitude, see Table 1. In that case the effects of thermal blooming would be negligible. The exponential decrease of α as a function of fluence has been observed experimentally in the case of water droplet evaporation for cloud clearing.

An indirect confirmation of the validity of our size distribution and absorption cross-section models comes by comparing α_o from Eq. (15) with the results in the Handbook of Optics. There a Yunge distribution and Mie scattering theory have been used. At 23 km visibility $N_o = 2.8 \times 10^3 \text{ particles/cm}^3$. At $\lambda = 1.06 \mu\text{m}$ for dry aerosols (30%), $n_i = 8 \times 10^{-3}$ and for soluble aerosols (70%), $n_i = 1.7 \times 10^{-2}$. With $a_o = 0.1 \mu\text{m}$ one finds from Eq. (15) $\alpha = 1.2 \times 10^{-7} \text{ cm}^{-1}$. The result in the Handbook of Optics is $\alpha = 1.1 \times 10^{-7} \text{ cm}^{-1}$. The table below shows an excellent agreement at different wavelengths where data is available.

Table 2: Comparison of Absorption Coefficients at Different Wavelengths

$\lambda(\mu\text{m})$	$\alpha(1.06)/\alpha(\lambda)$ Theory, Eq. (15)	$\alpha(1.06)/\alpha(\lambda)$ Handbook of Optics
10.6	1.68	1.97
3.392	4.95	4.86
0.6328	1.37	1.18
0.337	0.82	0.74
0.248	0.12	Not available

There is a clear distinction between the absorption coefficients of aerosols and the air. The heat is transferred from the aerosols to the surrounding air with a time delay given by the equilibration time. The α_a which enters the thermal blooming analysis is a measure of the rate of heat deposition in the air,⁽⁸⁾

$$\alpha_a = \frac{\rho_a C_a}{I} \frac{\partial T}{\partial t}, \quad (16)$$

where T is the temperature of the air. $\alpha_a I$ is the rate of heating per unit volume of air. To establish the relationship between α_a from (16) and α from (13) let us write the increase of the temperature in the air by solving Eqs. (1) and (2),

$$\Delta T(\bar{r}, \bar{r}_i, t, a_i) = \frac{I(\bar{r}_i) \sigma_A(a_i)}{4\pi K_a |\bar{r} - \bar{r}_i|} B \quad (17)$$

where

$$B(\bar{r} - \bar{r}_i, t) = \frac{2}{\sqrt{\pi}} \int_{\beta}^{\infty} \left\{ 1 - \exp \left[-\frac{t}{\tau_a} \left(1 - \frac{\beta^2}{\mu^2} \right) \right] \right\} e^{-\mu^2} d\mu ,$$

$$\beta = \frac{|\bar{r} - \bar{r}_i| - a_i}{\sqrt{4Dt}} , \quad D = \frac{K_a}{\rho_a C_a} .$$

The temperature increase at point \bar{r} and time t is due to an aerosol of radius a_i at a point \bar{r}_i . The air temperature due to an ensemble of particles is

$$\langle \Delta T \rangle = \sum_i \Delta T(\bar{r}, \bar{r}_i, t, a_i) . \quad (18)$$

If the intensity variation on a scale comparable to the interparticle distance is small and they are many particles in a volume d^3 , where d is the laser beam diameter, one can write $\langle \Delta T \rangle$ in the form of an integral,

$$\langle \Delta T(\bar{r}, t) \rangle = \frac{I(\bar{r})}{K_a} \int_0^{\infty} da f \sigma_A A(a, t) , \quad (19)$$

where

$$A(a, t) = \int_a^{\infty} \rho d\rho B(\rho, t) .$$

The time for diffusion of the air over scales of the order of a is $t_D = a^2/D$. With $D = 0.24 \text{ cm}^2/\text{sec}$, $a = 0.2 \text{ } \mu\text{m}$ one has $t_D = 1.7 \text{ nsec}$. At $t \gg t_D$ one can write

$$A(a, t) = D \left[t - \tau_a \left(1 - e^{-t/\tau_a} \right) \right] . \quad (20)$$

From Eq. (16) the thermal blooming absorption coefficient becomes⁽⁸⁾

$$\alpha_a(F, t) = \int_0^{\infty} da f(a, F) \sigma_A(a) \left(1 - e^{-t/\tau_a} \right) \quad (21)$$

By using the distribution function (12) one can find α_a as a function of time for different LAV laser intensities and wavelengths. The results are plotted in Fig. 7, where the absorption coefficient is normalized to that in the absence of vaporization. The LAV intensities are chosen at the stimulated rotational Raman threshold for atmospheric propagation to altitudes of 10 km (see Section 2.6). Note that at short times α_a rises linearly in time and it reaches a maximum when the vaporization threshold is reached. After that it falls off exponentially due to vaporization. For example, a KrF laser with $\tau_p = 1 \text{ } \mu\text{sec}$ and $I = 3 \text{ MW/cm}^2$ (fluence of 3 J/cm^2) will reduce the absorption coefficient by a factor of 50.

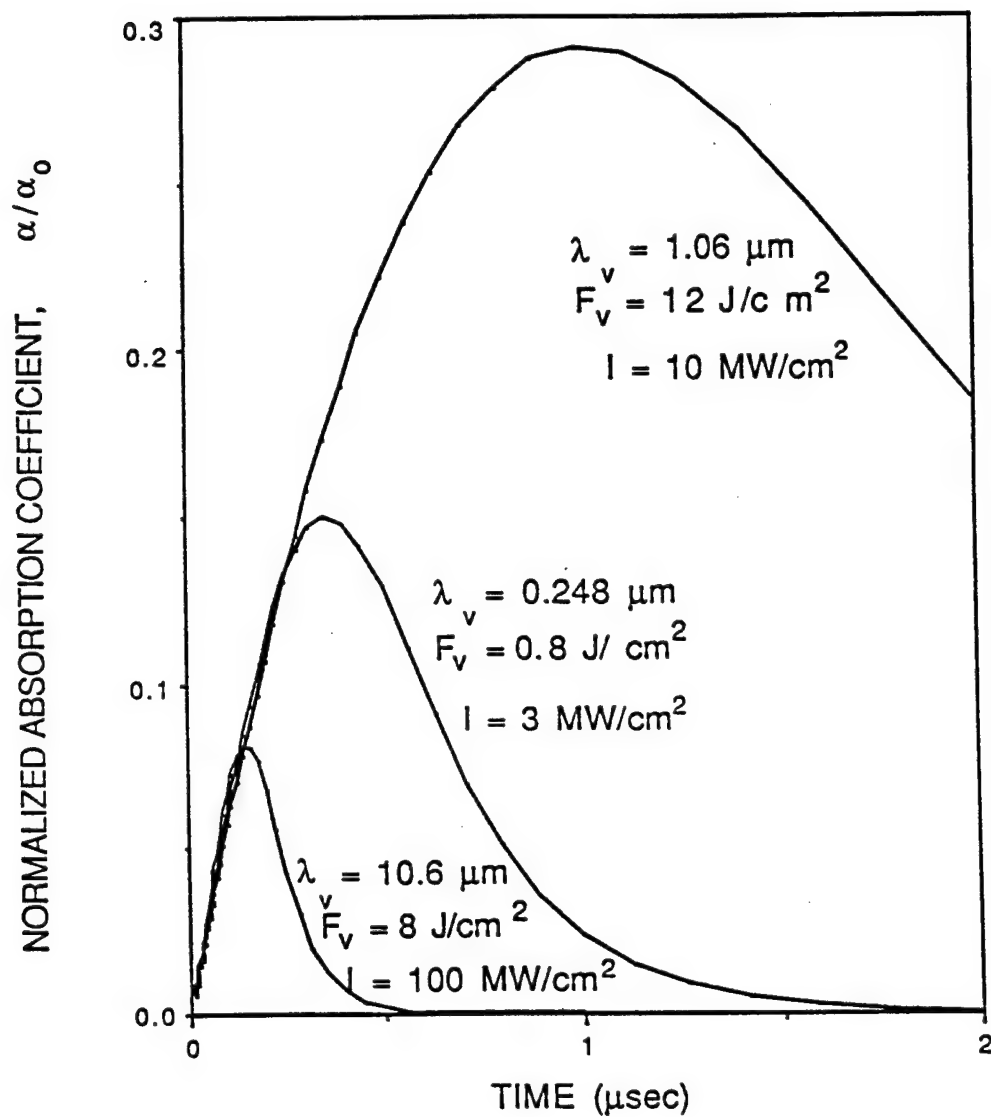


Figure 7: Absorption coefficient in air due to aerosols

2.5 PHASE DISTORTIONS DUE TO AEROSOL VAPORIZATION

The heat deposited in the aerosols and transferred to the air changes the local refractive index. Let us define $S = \delta(n - 1)/(n - 1)$, where n is the refractive index of the air. S induced by the LAV pulse is given by⁽²⁾

$$\left(\bar{\nabla}^2 - \frac{1}{C_s^2} \frac{\partial^2}{\partial t^2}\right) \frac{\partial S}{\partial t} = -\frac{\gamma - 1}{\gamma p} \bar{\nabla}^2 [\alpha_a(I, t) I] \quad , \quad (22)$$

where C_s is the sound speed, $\gamma = 1.4$ is the ratio of specific heats, p is the ambient pressure and I refers to the intensity of the LAV. The number of wavelengths of phase distortion in a propagation distance L is

$$\delta N = \frac{n - 1}{\lambda_v} \int_0^L S dz \quad (23)$$

Note that during the LAV pulse the phase distortion δN is in the transient thermal blooming regime and it is negligible. This means that the LAV does not have to be phase compensated for thermal blooming. δN is carried by the wind from the LAV guard-ring into the main HEL beam. One has to evaluate δN at times of the order of the wind clearing time of the guard-ring, $t_v \simeq d_v/V_W$. t_v is typically 0.1 sec and is much longer than the time for the sound wave to cross the guardring. In that case $\bar{\nabla}^2 S \gg C_s^{-2} \partial_t^2 S$ and the phase distortion becomes

$$\delta N = -\frac{(n - 1)(\gamma - 1)}{\lambda_v \gamma p} \int_0^L dz \int_0^{\tau_p} dt \alpha_a(I, t) I \quad (24)$$

From Eq. (21) α_a can be modeled by the expression

$$\alpha_a(I, t) = \alpha_o \exp\left(-\frac{It}{F_v}\right) \left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \quad , \quad (25)$$

where τ is the equilibration time during vaporizations,

$$\tau = \tau_a \exp\left(-\frac{2It}{3F_v}\right) \quad .$$

One takes into account the exponential decrease in the absorption coefficient and the effective time delay (τ) for the transfer of heat to the air. As seen from Fig. 7, τ is typically less than 1 μ sec. By integrating Eq. (24) with α_a from (25) one finds

$$|\delta N| = \frac{\beta}{2\pi} L \left\{ 1 - \exp\left(-\frac{I\tau_p}{F_v}\right) - \frac{I\tau}{I\tau + F_v} \left[1 - \exp\left(-\left(\frac{I}{F_v} + \frac{1}{\tau}\right)\tau_p\right) \right] \right\} \quad , \quad (26)$$

where

$$\beta = \frac{2\pi(n - 1)(\gamma - 1)}{\lambda_v \gamma p} \alpha_o(\lambda_v) F_v \quad .$$

When $\tau_p > \tau$, $I\tau < F_v$, which is typical for the vaporization regime, the result is simplified,

$$\delta N = \frac{\beta}{2\pi} L \left[1 - \exp\left(-\frac{I\tau_p}{F_v}\right) \right] \equiv \delta N_o + \delta N_1 \quad (27)$$

Significant vaporization occurs when $I\tau_p > F_v$ and the last term in Eq. (27) is small. The phase change is nearly constant across the beam. With α_o from Eq. (15), 3×10^3 particles/cm³, $a_o = 0.1 \mu\text{m}$ and $L = 2 \text{ km}$ one finds the LAV induced constant phase distortion at different wavelengths, $\delta N_o (10.6 \mu\text{m}) = 0.15$, $\delta N_o (1.06 \mu\text{m}) = 1.5$ and $\delta N_o (0.248 \mu\text{m}) = 6$. Clearly the KrF laser has the largest phase distortion, but even 6 waves are negligible for the HEL phase compensation adaptive optics. A different problem arises from the δN_1 term. Even when the spatially averaged $\delta N_1 \ll \delta N_o$, it introduces spatial scales from the turbulence induced intensity fluctuations of LAV. These scales are of the order of the coherence length, $r_o \sim \lambda^{5/6}$, and are much smaller for a KrF LAV. The actuator spacing of the deformable mirror for an HEL beam at $\lambda = 1.06 \mu\text{m}$ is determined by r_o which is typically 10 cm. Such a mirror does not compensate at scales corresponding to a KrF LAV with $r_o = 3 \text{ cm}$ if they exceed significantly those of the atmospheric turbulence. However, by increasing the KrF laser fluence the deleterious effects of small scale distortions can be minimized, as is now shown.

The figure of merit is the Strehl ratio which is determined by the mutual coherence function,

$$M_{12} = \langle \exp i(\psi(1) - \psi(2)) \rangle \quad (28)$$

The phases are evaluated at two points separated by a two-dimensional vector, $\bar{\Delta}$. $\langle \dots \rangle$ means ensemble average. The turbulence M_{12}^T is⁽¹¹⁾

$$M_{12}^T = \exp \left[-3.44 \left(\frac{\Delta}{r_o} \right)^{5/3} \right] \quad (29)$$

where the coherence length is $r_o^{-5/3} = 0.423 C_n^2 L (2\pi/\lambda)^2$. The LAV induced mutual coherence function from Eq. (27) is

$$M_{12} = \langle \exp \left\{ i\beta \int_0^L dz \left[\exp \left(-\frac{I(\bar{r}, z)\tau_p}{F_v} \right) - \exp \left(-\frac{I(\bar{r} + \bar{\Delta}, z)\tau_p}{F_v} \right) \right] \right\} \rangle \quad (30)$$

Note that in deriving Eq. (27) we have assumed that I is constant in z . In Eq. (30) we have used a general form $I(\bar{r}, z)$. The intensity correlation function for weak turbulence is

$$\langle \delta I(\bar{r}, z_1) \delta I(\bar{r} + \bar{\Delta}, z_2) \rangle = 2.24 C_n^2 k_v^{7/6} z^{11/6} \left(1 - 0.6 \left(\frac{\Delta^2}{\lambda_v z} \right)^{5/6} \right) \exp \left(-\frac{\xi^2}{2z^2} \right) \langle I \rangle^2$$

where

$$\delta I = I - \langle I \rangle, z = \frac{1}{2}(z_1 + z_2), \xi = z_1 - z_2 \text{ and } k_v = \frac{2\pi}{\lambda_v} \quad (31)$$

After a lengthy calculation one finds from Eqs. (30) and (31)

$$M_{12} = \exp \left\{ -0.13 \left[\beta L \frac{F}{F_v} \exp \left(-\frac{F}{F_v} \right) \frac{\lambda}{\lambda_v} \right]^2 \left(\frac{\Delta}{r_v} \right)^{5/3} \right\} \quad (32)$$

When the fluence is such, that the mutual coherence function M_{12} is larger than the turbulence M_{12}^T , the LAV induces phase changes smaller than those generated by turbulence alone. In that case the HEL compensation system will work and the LAV phase distortions can be neglected. From Eqs. (29) and (32) the requirement $M_{12} > M_{12}^T$ leads to the following constraint

$$0.2\beta L \frac{\lambda F}{\lambda_v F_v} \exp \left(-\frac{F}{F_v} \right) < 1 \quad (33)$$

From the discussion after Eq. (27) note that $\beta L/2\pi = 6$ at $\lambda_v = 0.248 \mu\text{m}$. At $\lambda/\lambda_v = 4$ from (33) one requires that $F/F_v \geq 5$, which is consistent with the requirement of a significant reduction in the absorption coefficient. At $\lambda_v = 1.06 \mu\text{m}$ the corresponding requirement would be $F/F_v \geq 1$; however, at $\lambda_v = 10.6 \mu\text{m}$ the small distortions would not be an issue.

2.6 LASER FOR AEROSOL VAPORIZATION (LAV)

In this section we describe the main characteristics of a laser designated to clear the atmospheric path of a HEL beam by aerosol vaporization. Its mission is to reduce the aerosol absorption by at least an order of magnitude over a cross section of a few square meters and up to altitudes of 10-20 km. This will permit the high power beam for BMD to propagate with significantly reduced phase distortion due to thermal blooming. The intensity of LAV is limited by the threshold for stimulated rotational Raman scattering in N_2 . The SRRS steady state gain coefficient is given approximately by g (cm/TW) = $2.5/\lambda$ (μm). Collisional broadening dominates over Doppler broadening up to altitudes of 50 km; therefore, to a good approximation g may be considered to be constant at altitudes below 50 km, and zero beyond. For an integrated gain, $G = g I_{th} h \simeq 30$ from the ground up to an altitude of $h = 10$ km, the threshold intensity is I_{th} (MW/cm^2) = 12λ (μm). In the case of a CO_2 wavelength one might not be able to operate near the Raman threshold because of optical breakdown in air (due to aerosols). The fluence of the LAV has to exceed F_v to vaporize the particles, and it has to deliver the energy for pulselengths $\tau_p < \tau_a$, the particle equilibration time. This will insure effective heating of the aerosols and not the surrounding air. The requirement for the LAV pulselength is $\tau_a > \tau_p > \tau_c = F_v/I_{th}$. Note that $\tau_a = 1.3 \mu\text{sec}$ for the dominant particles with radius $a = 0.2 \mu\text{m}$. At the KrF wavelength $F_v = 0.8 \text{ J}/\text{cm}^2$ and $\tau_c = 0.3 \mu\text{sec}$. For $\lambda = 1.06 \mu\text{m}$, $F_v = 12 \text{ J}/\text{cm}^2$ and $\tau_c = 1 \mu\text{sec}$. At the CO_2 wavelength $F_v = 8 \text{ J}/\text{cm}^2$ and $\tau_c = 7 \times 10^{-2} \mu\text{sec}$. Even at $I(10.6 \mu\text{m}) = 40 \text{ MW}/\text{cm}^2$ one has $\tau_c = 0.2 \mu\text{sec}$, which may be a reasonable regime to operate to avoid optical breakdown. Clearly, the KrF and CO_2 wavelengths are well suited for aerosol vaporization, while the $1 \mu\text{m}$ wavelength is a borderline case.

As a spatial format for LAV, consider a guard-ring of thickness d_v , surrounding the main HEL beam of diameter d (Fig. 8). In this format the beam will be cleared independently of the wind direction and the wind shear. The area cleared is ($d \gg d_v$) $A_v \simeq \pi d d_v$.

The pulse repetition rate of the LAV is determined by the wind velocity and d_v , $\text{PRF} = V_W/d_v$. For $V_W = 5$ m/sec and $d_v = 0.5$ m one finds $\text{PRF} = 10$. At this repetition rate all aerosols moving through the guard-ring are irradiated by at least one LAV pulse. Thus, after a wind clearing time, the whole FEL beam will propagate at a reduced absorption in steady state. The average power of the LAV can be estimated as

$$P_v = \pi d \tau_p V_W I \quad , \quad (34)$$

where I is the peak LAV intensity. Since $I \tau_p > F_v$, for vaporization one finds

$$P_v \geq \pi d V_W F_v \quad (35)$$

For an FEL-TIE beam diameter of 4 m one finds $P_v \geq 0.5$ MW at $\lambda = 0.248 \mu\text{m}$. At $\lambda = 1.06 \mu\text{m}$, $P_v \geq 7.5$ MW and for $\lambda = 10.6 \mu\text{m}$, $P_v \geq 5$ MW. Again the KrF wavelength is the most promising, but even at the other wavelengths the power of the LAV is a small fraction of the 100 MW plus GBL power. The scheme of using LAV for clearing up the beam path appears to be very cost effective.

2.7 SCALING OF THE CRITICAL HEL POWER WITH LAV

The atmospheric absorption as a function of altitude is of the form

$$\alpha = \alpha(o) \exp\left(-\frac{z}{L}\right) \quad , \quad (36)$$

where L is of the same order as the thickness of the turbulence layer, $L_T \simeq L \simeq 2$ km. The strength of the thermal blooming is described by a distortion number,

$$N_D = 4\pi \frac{(n-1)(\gamma-1)\alpha(o)L}{\gamma p V_W \lambda d} P \quad , \quad (37)$$

where P is the average laser power, d is the beam aperture, n is the refractive index, $n-1 = 3 \times 10^{-4}$ at 1 atm and p is the ambient pressure. For laser powers in the MW range and beam diameters of a few meters N_D is typically $N_D \geq 10^2$. The phase compensation system can give Strehl ratios approaching one only when N_D is below a certain threshold value, $N_{D_{th}}$. When one neglects wind shear, $N_{D_{th}}$ can be evaluated numerically and analytically, taking into account phase compensation for atmospheric turbulence and thermal blooming. The result is

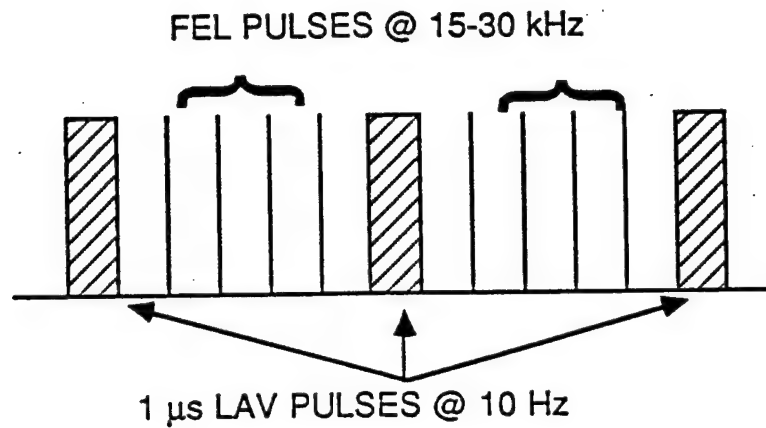
$$N_D \simeq 16 N_T^{5/12} \quad , \quad (38)$$

where $N_T = r_o^2/\lambda L$ is the turbulence coherence length Fresnel number. The threshold distortion number from Eqs. (37) and (38) leads to a critical laser power for the propagation of a ground based laser,

$$P_c = 1.3 \frac{\gamma p V_W \lambda^{7/12} r_o^{5/6} d}{(n-1)(\gamma-1) L^{17/12} \alpha(o)} \quad (39)$$

At a given aperture and wavelength only laser powers $P < P_c$ can propagate through the atmosphere without serious degradation in optical beam quality. Note that $P_c \propto d$, a result

- TEMPORAL FORMAT OF LAV AND FEL



- SPATIAL FORMAT

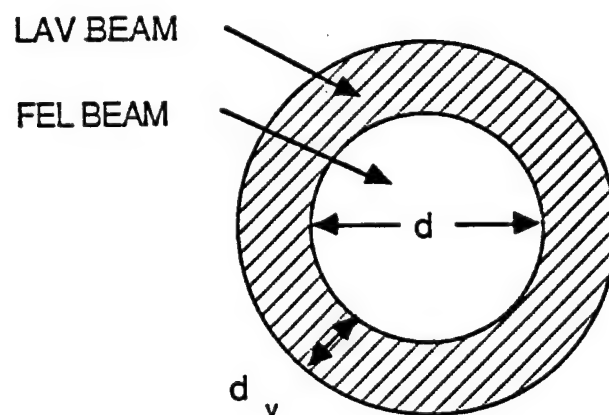


Figure 8: Temporal and spatial pulse format for vaporizing aerosols

which is very unfavorable for scaling to the large powers necessary for BMD applications ($P \geq 100$ MW). At $\lambda = 1.06 \mu\text{m}$, $r_o = 10$ cm, $V_W = 5$ m/sec, $L = 2$ km, $\alpha(o) = 2 \times 10^{-7} \text{ cm}^{-1}$, the critical power is plotted as a function of beam diameter in Fig. 9. Note that at $d = 10$ m only 10 MW of power can be transmitted through the atmosphere with Strehl ratios close to 1. More realistic models, including the effect of wind shear appear to give an increase of P_c . The scaling in that case is still the subject of an active study. On the other hand, a defensive system should be robust and work well under stressful conditions and it should not rely on favorable weather. We consider the scaling (39) a conservative estimate which one might be forced to accept as a guide for the design of a GBL.

The only certain way to increase the critical power is to reduce significantly the absorption coefficient. This can be achieved with a LAV of modest powers. Note the exponential dependence of α on LAV fluence, Eq. (14). By using the power of LAV in a guard-ring, Eq. (34), one finds the aerosol absorption coefficient with vaporization.

$$\alpha_v = \alpha(o) \exp \left(-\frac{P_v}{\pi V_W d F_v} \right) \quad (40)$$

Now one can replace $\alpha(o)$ in Eq. (39) with the reduced value α_v . The scaling law of the critical HEL power becomes a function of beam diameter and LAV power. The result for a KrF LAV is shown on Fig. 9 at $P_v = 2$ MW. Note the enormous (> 100 MW) HEL powers at small beam diameters. Unfortunately, in practice, even in the presence of LAV one can not propagate such large laser powers through the atmosphere because of the inherently low duty factors of the HEL and the threshold for stimulated rotational Raman scattering (SRRS) mentioned in Section 2.6. At duty factors $< 10^{-3}$, 1 kW/cm² of average intensity leads to peak intensities in excess of 1 MW/cm². The HEL is constrained by a Raman threshold for the atmosphere to altitudes of 50 km, not the 10 km altitude sufficient for the LAV. The peak intensity threshold for an HEL is

$$I_{th}(\text{MW/cm}^2) = \frac{2.5}{\lambda(\mu\text{m})} \quad (41)$$

In terms of average power the threshold becomes

$$P_{th}(\text{MW}) = \frac{19.6}{\lambda(\mu\text{m})} d^2(\text{m}) \tau_L(\mu\text{sec}) \text{PRF}(\text{kHz}) \quad (42)$$

The units for the various quantities are noted in brackets. For a given beam diameter only $P < P_{th}$ can propagate without degradation from Raman scattering. A HEL with $\tau_L = 50$ nsec, PRF = 5 kHz leads to the Raman threshold curve shown on Fig. 9 with the "forbidden" region shaded. By way of example, a KrF LAV at 2 MW of power can clear a channel for the propagation of 100 MW of HEL power at beam diameters of 4-5 m.

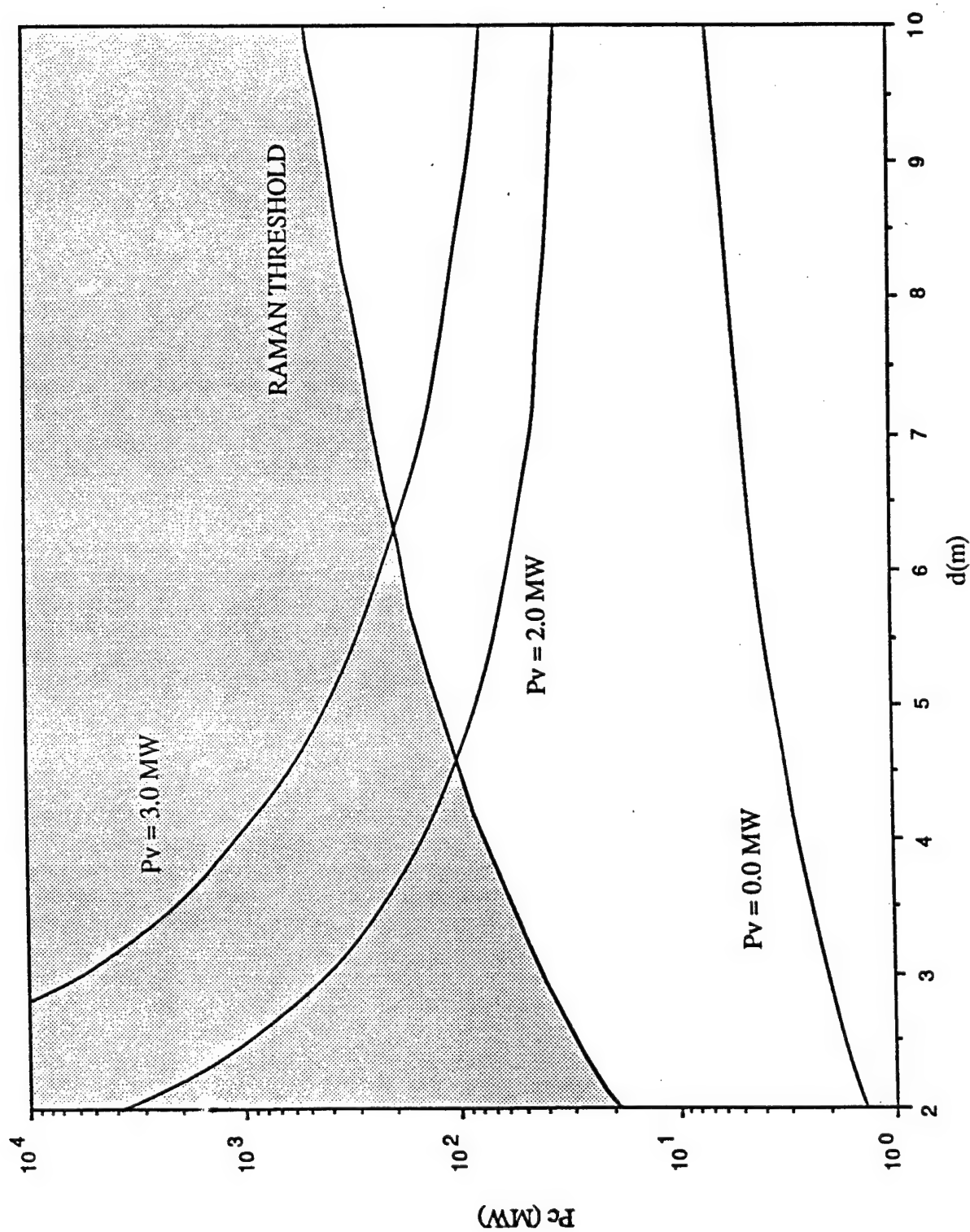


Figure 9: Critical power of HEL with LAV at 0.248 μm wavelength, $F_v = 0.8 \text{ J/cm}^2$ (no wind shear)

3.0 SBIR PHASE II PROGRAM

SRL will propose an SBIR Phase II program to determine the reduction of the atmospheric aerosol absorption by aerosol vaporization. The success of this program will have a significant and immediate impact on the design of a ground based laser for ballistic missile defense.

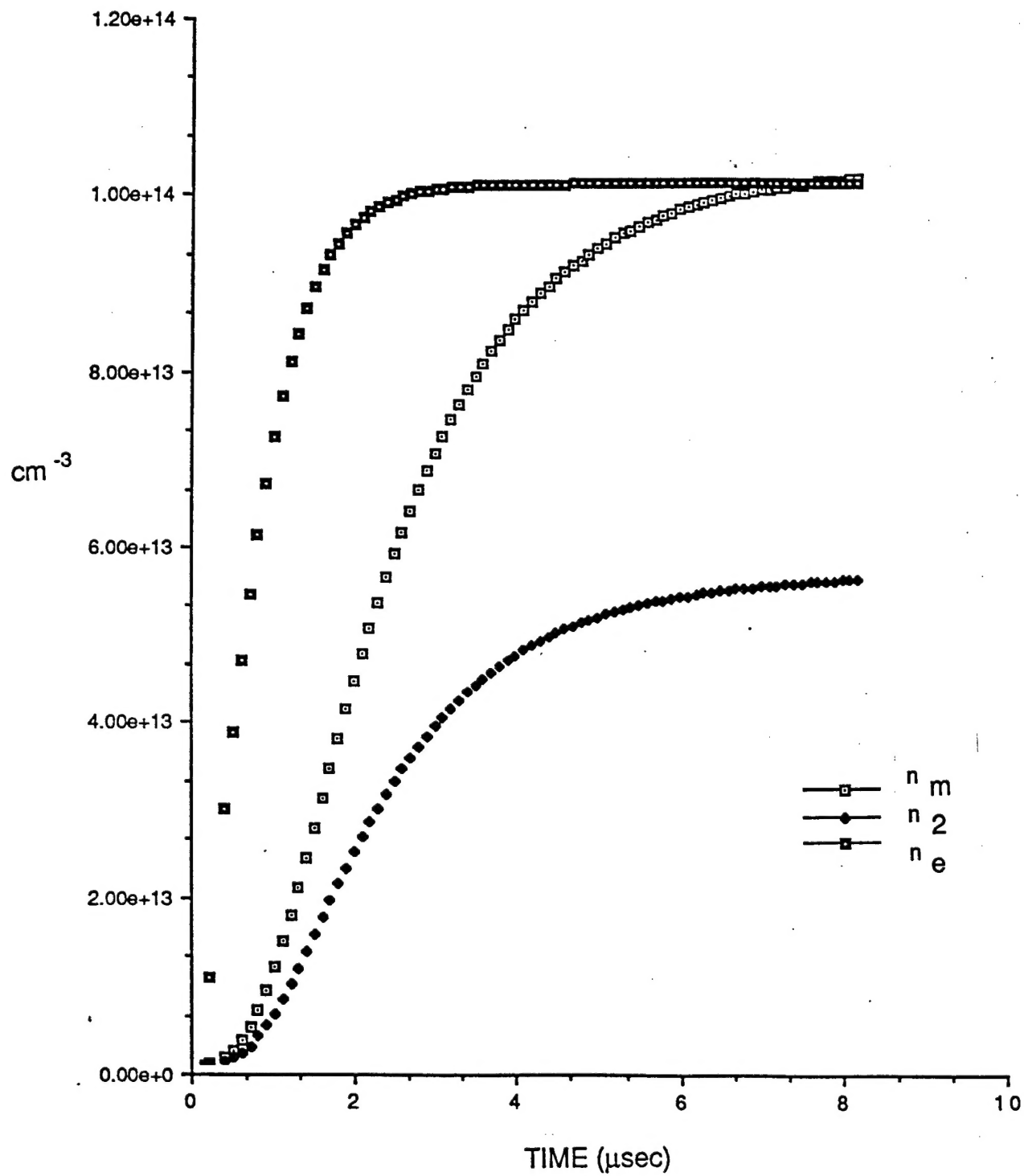
CONCLUSION

As has been discussed in this report, propagation of ground-based, high-energy laser (HEL) beams through the atmosphere at a laser wavelength of $\lambda_L = 1.06 \mu\text{m}$ is limited by thermal blooming due to aerosol absorption. The scaling of critical laser power with beam diameter requires that the aperture size exceed 20 m for average laser powers of 100 MW.

In this SBIR Phase I report, Science Research Laboratory has shown that this problem may be solved by vaporizing the aerosols with a designated laser for aerosol vaporization (LAV). The dependence of vaporization on fluence and wavelength was determined. In particular, it was shown that a LAV wavelength $\lambda_v = 1.06 \mu\text{m}$ and intensity of $10 \text{ MW}/\text{cm}^2$ yields a reduction by a factor of 5 at $2 \mu\text{sec}$, corresponding to $20 \text{ J}/\text{cm}^2$ of laser fluence per pulse. The best LAV wavelength appears to be that of a KrF laser, $\lambda_v = 0.248 \mu\text{m}$. For this wavelength, an intensity of $3 \text{ MW}/\text{cm}^2$ and a pulse duration of $1 \mu\text{sec}$, corresponding to a fluence of $3 \text{ J}/\text{cm}^2$ per pulse, reduces aerosol absorption by a factor of 50. Such a decrease in the absorption coefficient eliminates the difficulties associated with thermal blooming.

The dependence of the critical HEL power on the beam aperture diameter d has been determined in the presence and absence of LAV, assuming no wind shear. Without vaporization the scaling law is pessimistic—one can propagate less than 10 MW average power at $d = 10 \text{ m}$. If one uses a KrF laser at an average power of 2 MW, a pulsewidth of $1 \mu\text{sec}$, and a pulse repetition frequency (PRF) of 10 Hz, the critical power at $d = 5 \text{ m}$ is 100 MW. This greatly alleviates the thermal-blooming problem.

Science Research Laboratory will shortly submit a Phase II SBIR proposal to experimentally test and demonstrate the LAV concept.



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